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# Compilation of Published PM2.5 Emission Rates for Cooking, Candles and Incense for Use in Modeling of Exposures in Residences

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## Disclaimer

# Abstract

A recent analysis of health impacts from air pollutant inhalation in homes found that $PM_{2.5}$ is the most damaging at the population level. Chronic exposure to elevated $PM_{2.5}$ has the potential to damage human respiratory systems, and may result in premature death. $PM_{2.5}$ exposures in homes can be mitigated through various approaches including kitchen exhaust ventilation, filtration, indoor pollutant source reduction and designing ventilation systems to reduce the entry of $PM_{2.5}$ from outdoors. Analysis of the potential benefits and costs of various approaches can be accomplished using computer codes that simulate the key physical processes including emissions, dilution and ventilation. The largest sources of $PM_{2.5}$ in residences broadly are entry from outdoors and emissions from indoor combustion. The largest indoor sources are tobacco combustion (smoking), cooking and the burning of candles and incense. Data on the magnitude of $PM_{2.5}$ and other pollutant emissions from these events and processes are required to conduct simulations for analysis.

The goal of this study was to produce a database of pollutant emission rates associated with cooking and the burning of candles and incense. The target use of these data is for indoor air quality modeling.

Potentially relevant data were identified through searches of relevant terms on citation indexing services that together list peer-reviewed journal articles and some government-sponsored research reports. Studies that appeared to have relevant data were examined. When relevant data were identified, they were compiled into a master database that has been used to produce distributions of emission rates (mass of pollutant emitter per unit time) related to various factors that impact emission rates from cooking and food; these include food type, oil type, cooking method, and stove type. The emission rates data were aggregated into a database of cooking and candle burning emission rates for use in indoor air quality modeling.

Although many papers explore the impact of cooking on indoor air quality, only a few of them report $PM_{2.5}$ emission rate data and even fewer provided detailed cooking conditions. We collected cooking emission rate data for 541 cooking events from 13 studies and, by analyzing and comparing them, we found that the type of cooking device used (i.e. microwave vs. stove) and the type of cooking (cooking in the oven vs. cooking on the stovetop) resulted in distinctly different distributions of $PM_{2.5}$ cooking emission rates. The remaining cooking parameters that showed significant impacts on emission rates during individual studies, such as fuel type of stove and cooking method, did not show significant differences in emission rates when data from multiple studies were compared. Incense burning was shown to have higher $PM_{2.5}$ emission rates than candle burning for the limited data available. This paper also includes an extensive annotated bibliography of the papers reviewed of indoor cooking and candle burning emissions, which can be useful for pollutant source research and assessments of indoor air quality.

# Introduction

Indoor air quality (IAQ) is a major health concern. Research indicates that an average of 90% of the populations lifetime is spent indoors[1], and over 2/3 of that time in homes. Air pollutant concentrations in many homes exceed health-based standards for chronic and acute exposures[2] and numerous studies have noted the importance of the indoor environment to cumulative air pollutant exposure[3,4]. Logue et al. applied an impact assessment methodology to distributions of pollutant concentrations measured in residences[5]. The study identified $PM_{2.5}$ as the most damaging pollutant on a population average in U.S. homes. The European EnVIE study also identified $PM_{2.5}$ as the most damaging indoor air pollutant in Europe[6].

$PM_{2.5}$ refers to the mass of particulate matter that is below 2.5 micrometers in diameter. $PM_{2.5}$ has been shown to penetrate into the alveoli and lodge deeply into the lungs and even enter in the blood stream. Several studies have discussed the serious health impact of $PM_{2.5}$ (e.g, Schlesinger 2007; Pope et al. 2002; Künzli et al. 2004; and Miller et al. 2007 ). Based on the adverse health effects of $PM_{2.5}$, the US EPA includes $PM_{2.5}$ mass in the suite of pollutants whose concentrations are regulated in the ambient atmosphere[7]. Geographical areas that do not meet these standards, non-attainment areas, can face large fees and penalties. There are no similar air quality regulations for indoor air, however it stands to reason that IAQ indoors should minimally meet the regulated concentration for the ambient atmosphere. A recent study has shown measured $PM_{2.5}$ concentrations in a substantial fraction of homes in the US exceed outdoor air quality standards.

In order to develop a better understanding of exposures and aid in the development of policies to improve residential indoor air quality, the Lawrence Berkeley National Lab (LBNL) is in the process of developing a data-driven, physics-based modeling framework to assess the energy and indoor air quality impacts of ventilation and pollutant mitigation measures on the U.S. population for both new and retrofitted homes. One major component of this modeling work is the Indoor and Exposure Relevant Concentration (IERC) Model. For each home, the IERC executes a single-zone mass balance to determine indoor pollutant concentration profiles based on indoor emissions, outdoor pollutant entry, indoor removal based on air exchange rates predicted from home characteristics, and other removal processes such as deposition. The model then determines the exposure relevant indoor concentration by overlapping occupancy patterns with the calculated concentrations profiles. Given the importance of the health effects of $PM_{2.5}$ and the observation that many homes have elevated $PM_{2.5}$ concentrations, it is a top priority to include sources that drive $PM_{2.5}$ concentrations in homes into the IERC model. The goal is to aggregate a set of emission rates that we can use in conjunction with activity data to get overall emission schedules.

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[1] Klepeis et al. "The National Human Activity Pattern Survey (NHAPS)."
[2] Logue et al., "Hazard Assessment of Chemical Air Contaminants Measured in Residences."
[3] Weisel et al., "Relationship of Indoor, Outdoor and Personal Air (RIOPA) Study."
[4] Samet, "Indoor Air Pollution."
[5] Logue et al., "A Method to Estimate the Chronic Health Impact of Air Pollutants in US Residences."
[6] EnVIE, "Co-ordination Action on INdoor Air Quality and Health Effects."
[7] EPA, "National Ambient Air Quality Standards (NAAQS)."

Capturing every source of $PM_{2.5}$ in residences accurately would be prohibitively time consuming and resource intensive, therefore it is important to prioritize the $PM_{2.5}$ sources to add to the database. Chao and Cheng[8] conducted a source-apportionment analysis in which they listed five main sources of $PM_{2.5}$ indoors: smoking, cooking, incense burning, human activities (such as cleaning), and outdoor contributions. Kamens et al.[9,10] reported that cooking was the most significant source of small particles (< 2.5 μm). These reports emphasized the importance of assessing cooking related indoor particles emissions. Glytsos et al. reviewed the $PM_{2.5}$ emission characteristic from candle burning and determined that, when present, candles can be the primary source of ultrafine particles.[11] Based on these indoor source assessments, we have focused our initial $PM_{2.5}$ emissions database development on aggregating cooking, candle, and incense emission data to develop the preliminary $PM_{2.5}$ emission rate database for the IERC model.

This paper reports the results of the initial efforts to develop an emissions database for cooking and candle burning in residential U.S. environments. The work focused on collecting $PM_{2.5}$ emission rate data but also included any emission rate data for other pollutants included in cooking emissions studies. This paper presents the result of a literature review used to aggregate existing information on emissions from indoor residential cooking activities and candle and incense burning. Adequate emission rates from these papers were compiled into a $PM_{2.5}$ emission rate database. Critical areas where data is lacking are also identified and an extensive annotated bibliography of the papers reviewed is included.

# Approach

## *Overview of Emissions Terminology*

The ultimate goal of this work was to develop a database of emissions data that could be used in conjunction with behavior data to develop time dependent profiles of the cooking and candle/incense burning emission rates for individual homes. To do this we aggregated data from papers that reported both emission rates as well as those that reported emission factors. Emission factors are pollutant emissions characterized in relation to a discrete activity event or in relation to some other measure of activity. A typical form of an emission factor is a mass of pollutant emitted per unit of activity. A discrete event could be the cooking of a meal such as breakfast, or the cooking of a particular dish, such as frying a hamburger. For the latter, the emission factor could have units of mass of $PM_{2.5}$ emitted per hamburger fried. Emission factors are sometimes related to the scale of activity. For the hamburger example, the emission factor could be expressed in units of mass of $PM_{2.5}$ emitted per mass of hamburger fried.

For the purposes of modeling time-dependent pollutant concentrations in homes, it is often useful to have emission rates in the form of mass of pollutant emitted per time increment and to combine this with an activity duration and schedule. Continuing with the previous example, we could convert the emission factor of mass of unit emitted per hamburger

8 Chao and Cheng, "Source Apportionment of Indoor PM2.5 and PM10 in Homes."
9 Kamens et al., "A Study of Characterize Indoor Particles in Three Non-smoking Homes."
10 He et al., "Contribution from Indoor Sources to Particle Number and Mass Concentrations in Residential Houses."
11 Glytsos et al., "Characterization of Particulate Matter Concentrations During Controlled Indoor Activities."

cooked to mass of PM2.5 emitted per unit time by dividing by the duration of the event. It is important to note that for activities of short duration, such as the frying of a hamburger, it may be most straightforward in some cases to just express the emission factor in terms of the event.

There is no single “right” way to express emissions for indoor air quality modeling. Rather, it is valuable to have information in formats that can be aligned with available activity data since activity data is often more difficult to obtain. Consider the example of candles. It may be possible to obtain estimates of the frequency of candle use in a home, but more challenging to obtain data on the duration of each event, and all but impossible to get direct estimates of the mass of candle consumed during each event. The duration of use may vary by up to an order of magnitude per event, i.e. enough that the emission factor should have more resolution than mass emitted per event. More useful would be an emission rate that reflects an average or typical consumption rate.

For this work, the emission data recorded in our database, which we will refer to as emission rates, are in units of mass (micrograms) per unit time (hours) either for a specific event such as cooking dinner which would be inclusive of all cooking emissions for dinner or in terms of mass (micrograms) per unit time (hours) per unit consumed (per candle burned or hamburger cooked). Emission rates are per unit consumed must be multiplied by the number of units emitting at a given time. For example, if you have the emission rate per unit time for a candle, you would need to know how many candles are burned at a given time. For all of the emission rate entries, the duration of the event must be specified.

## *Literature Review of Particle Emissions*

The initial step of this work was a literature review of studies reporting measurements of particles from indoor cooking activities and candle and incense burning. The review was conducted to identify all existing data that are suitable for our purposes while at the same time reviewing the existing literature.

The ISI web of knowledge database was used as the primary search engine. The California Energy Commission Reports database and the EPA exposure factors handbook[12] were also searched. The search was conducted using terms that can describe cooking, candle or incense emissions. Key words and phrases used with the web of knowledge included combinations of “cooking emission” “indoor air quality” “PM” “residential” “frying” “exposure” “emission rate” “fume” “particle” “stove” “oil” "candle" and "incense". This search yielded over 60 potentially useful articles of which 13 had cooking emissions data for inclusion in the database and 2 had useful candle and incense burning data. We included all papers in the database that reported emissions rates either in terms of unit mass emitted per unit time or unit mass emitted per unit time per amount of food cooked. We also included papers where emission rates could be calculated using data presented in the paper. The annotated bibliography includes all papers that yielded useful information about the impact of cooking on emissions whether or not they contained useful data for inclusion in the database.

[12] “Exposure Factors Handbook| Human Health Risk Assessment | Risk Assessment Portal | US EPA.”

Of the articles collected, relatively few papers reported actual cooking emission rates in the US and countries with similar lifestyles. Papers that did not contain useful cooking emission rates investigated the impact of cooking in countries that use wood or biomass fuel[13,14,15], reported particle number count but not particle mass[16], and reported concentrations only with insufficient information to calculate emissions rates for inclusion in our database[17,18,19]. For the papers that did report emissions data, the number that contain details of the cooking events is limited with important details missing. For example, He et al. reported the particle number and mass concentration emission rates from cooking in residential houses, but didn't describe details of the type of food cooked or how it was prepared. These are important parameters that impact the emission rate. Without knowing the mass of food, the appliance they have used, or other parameters it is difficult to compare the reported $PM_{2.5}$ emission rate to similar cooking experiments in other papers.

One key challenge to compiling data on pollutant emissions associated with cooking is that there is no single unit of activity that is obviously the best choice for all cooking-related activities. Reflecting this, the literature on cooking-related pollutants presents results in a variety of forms. The most common and least useful form is to report the concentrations that result from a given cooking activity under the particular conditions that applied at the time of measurement. Measured concentrations can be combined with other data to calculate emission rates. Without that other data, the measured concentrations are not themselves helpful in extrapolating to other conditions.

## *Calculation of Emission Rate*

Emission factors or rates are the unit of mass emitted per unit time for a specific activity and, for the most part, cannot be measured directly. Two common methods of measuring emission rates are: 1) to measure the mass of the pollutant source over time and calculate the rate of change in mass per unit time if the chemical composition of emissions is known relative to the source or 2) to measure the concentration in a confined space over time and calculate the change in mass in the room per unit time. Determining the emission rate of cooking almost exclusively uses the second method because the composition of the emissions varies as a function of the cooking conditions and the chemical composition of the source is rarely known. If the room is sealed, and there are no other loss mechanisms, the emission rate can be calculated using the following equation:

$$G = V * (C_{t=end} - C_{t=start})/\Delta T \tag{1}$$

Where: $G$ = pollutant emission rate
$V$ = volume of sealed measurement space

[13] Parikh et al., "Exposure from cooking with biofuels."
[14] Balakrishnan et al., "Daily average exposures to respirable particulate matter from combustion of biomass fuels in rural households of southern India."
[15] Albalak et al., "Indoor respirable particulate matter concentrations from an open fire, improved cook stove, and LPG/open fire combination in a rural Guatemalan community."
[16] Afshari, Matson, and Ekberg, "Characterization of Indoor Sources of Fine and Ultrafine Particles."
[17] Kabir and Kim, "An investigation on hazardous and odorous pollutant emission during cooking activities."
[18] Huboyo, Tohno, and Cao, "Indoor PM(2.5) Characteristics and CO Concentration Related to Water-Based and Oil-Based Cooking Emissions Using a Gas Stove."
[19] Abt et al., "Characterization of Indoor Particle Sources."

$C_{t=start}$ = concentration at start of measurement period
$C_{t=end}$ = concentration at end of measurement period
$\Delta T$ =duration of experiment

Measuring $PM_{2.5}$ emission rates in homes with multiple pollutant sources is much more complicated. House ventilation introduces pollutants from the outdoor environment indoors, complicating the separation of sources. Moreover, there are appreciable first order losses of $PM_{2.5}$ indoors due to deposition and possible removal from the operation of mechanical ventilation systems.

Many of the reviewed studies that explored the impact of cooking on indoor air quality did not specifically report emission rates. When a study did not report the emission rate of cooking events but had sufficient data to calculate the emission rate, the reported mass concentrations were converted to emission rates. For instance, the article by Zhang et al.[20] reported concentrations of ultrafine particles and other air pollutants emitted by cooking activities that enabled the calculation of emission rates. The report provided the average mass concentration of $PM_{2.5}$ during cooking activities, home volume, and air exchange rate for each house. We used a steady state mass balance equation that included air exchange rate of the home and a first order lost rate to calculate the emission rate:

$$C_{PM2.5,in} = \frac{k_a P}{k_a + k_d} * C_{PM2.5,out} + \frac{G}{V(k_a + k_d)} \quad (2)$$

Where: $C_{PM2.5}$ = residential $PM_{2.5}$ concentration ($\mu g/m^3$)
P = $PM_{2.5}$ penetration coefficient
$k_a$ = air exchange rate ($h^{-1}$)
$k_d$ = $PM_{2.5}$ indoor decay rate ($h^{-1}$)
G = indoor generated $PM_{2.5}$ emission rate ($\mu g/h$)
V = building volume ($m^3$)

During cooking events, we assume that outdoor concentrations do not contributed significantly to indoor concentrations because of high cooking emission rates. Fortmann et al[21] cooking tests showed indoor concentrations that were significantly higher than outdoor concentrations even in high pollution areas. Omitting the outdoor contribution to indoor $PM_{2.5}$ we obtain:

$$G = V(k_a + k_d) * C_{PM2.5,in} \quad (3)$$

Assuming $k_d$ to be 0.27 $h^{-1}$ [22], and a room height of 2.5 meters, we calculated $PM_{2.5}$ emission rate ranges from 6.8E2 to 5.8E4 micrograms per hour for the 14 cooking experiments conducted. In addition to $PM_{2.5}$ emissions, other pollutant emission rates resulting from indoor cooking activities such as CO, NO, $NO_2$, and other volatile organic compounds, were collected using the same approach.

[20] Zhang et al., "Measurement of Ultrafine Particles and Other Air Pollutants Emitted by Cooking Activities."
[21] Fortmann et al., "Indoor Air Quality: Residential Cooking Exposures. California Air Resources Board Final Report."
[22] Michael et al., "Air Pollution Exposure Model for Individuals (EMI) in Health Studies: Evaluation of Indoor Air Quality Model for Particulate Matter."

Two meat cooking studies reported emission rates as a function of the mass of meat cooked. These emissions rates were included in the database as a function of mass cooked[23,24]. When using these emission rates in the IERC model, they will be multiplied by the number of home occupants and the average meat consumption rate per person in the home as reported by the EPA exposure factors handbook.

Several reports of particle emission rates in restaurants were reviewed. However, insufficient information about cooking frequency or total food mass was provided to enable the conversion of the data to emission rates and were not included in the database.

# Summary of Results

Among the papers reviewed, 13 reports of cooking emissions and 2 reports of candle emissions were included in the database and are listed in Table 1. Summary statistics compiled for the database of $PM_{2.5}$ emission rates are provided in tables below. All cooking information from these papers was included in the database, including information like food and oil type, cooking temperature, appliance, cooking methods. However, very few individual database entries had all of this data. An annotated bibliography of the papers included in the database, including papers that did not have emissions data but were relevant to residential cooking and candle and incense burning, is included in the appendix.

*Table 1: Studies included in emission database*

| **Cooking Emission Studies** | |
|---|---|
| Buonanno et al. 2009 | McDonald et al. 1995 |
| Burke et al. 2001 | Olson et al. 2005 |
| Dennekamp et al. 2001 | Schaueret al. 1999 |
| Evans et al. 2008 | Seaman et al. 2009 |
| Fortmann et al. 2001 | Torkmahalleh et al. 2012 |
| He et al. 2004 | Zhang et al. 2010 |
| Kabir et al. 2011 | |
| **Candle and Incense Studies** | |
| Jette, et al. 2002 | Stabile et al. 2012 |

## *Cooking Emissions*

The assembled emission rate database contains 522 cooking tests from 13 papers. Most of the data comes from Fortmann et al. and Olson et al[25]. Fortmann et al . reported the most detail for cooking conditions, such as cooking temperature, oil and fuel species, air exchange rate, and house dimension. The remaining papers had only a fraction of this level of detail. Some of the papers, such as Fortmann et al., present results from specific cooking

[23] McDonald et al., “Emissions from Charbroiling and Grilling of Chicken and Beef.”
[24] Seaman, Bennett, and Cahill, “Indoor acrolein emission and decay rates resulting from domestic cooking events.”
[25] Olson and Burke, “Distributions of PM2.5 Source Strengths for Cooking from the Research Triangle Park Particulate Matter Panel Study.”

tests conducted in a laboratory setting and thus provide detailed descriptions of the experimental setup. Other reports, such as Olson et al., report emissions data recorded as part of a longer home monitoring study and thus had to rely on occupant diaries of the day's events to report details of cooking events. Table 2 shows what types of data were reported for each of the cooking emission events included in the database. Table 2 shows that geographic location is commonly provided, while few studies report details on cooking temperature and oil type. Of the cooking conditions reported, reviews of individual cooking studies indicated that there are four high impact cooking conditions (HICCs) that significantly influence emission rates: stove type, cooking method, oil type, and food type. When the aggregate emission data from the emission rates database were inter-compared, the results did not show the same effect of the HICC as observed in individual studies.

*Table 2: Summary of available data for cooking emissions*

| Summary of available data | | |
|---|---|---|
| Studies that reported | Number of Reports | Cooking Tests |
| Food types | 8 | 107 |
| Cooking temperature | 5 | 38 |
| Oil type | 5 | 58 |
| Cooking method | 9 | 330 |
| Stove type | 5 | 293 |
| Location (City, State) | 11 | 531 |
| Air exchange rate | 4 | 83 |
| $PM_{2.5}$ | 7 | 501 |
| PM10 | 1 | 58 |
| CO | 2 | 64 |
| NO2 | 2 | 63 |
| Other pollutants | 9 | |

## *Results from Individual Cooking Studies*

As noted above, individual cooking studies indicated that HICCs have the most significant impact on the emission rate of $PM_{2.5}$. This section discusses results from individual studies with regards to the impact of different cooking parameters or conditions on emission rates.

Several studies identified food type as having a strong impact on emission rates due to the chemical makeup of the food. Thiébaud et al.[26] found a relationship between the mass loss of food and the total emission during cooking events. Within the same cooking method, foods that easily lose water (bacon for example) were found to have greater emission rates than those having good water-retention characteristics. Other studies found a relationship between food fat proportion and particle emission rates. This relationship is reflected in individual studies that observed that cooking meat releases more particles than cooking vegetables with all other cooking variables held constant. Related experiments in Buonanno's[27] and Huboyo's reports showed the influence of temperature on cooking emissions with higher cooking temperature leading to higher emission rates. Zhang et al.

[26] Thiébaud et al., "Airborne Mutagens Produced by Frying Beef, Pork and a Soy-based Food."

[27] Buonanno, Morawska, and Stabile, "Particle emission factors during cooking activities RID B-4140-2011."

performed repeated cooking experiments at two cooking temperatures described as medium and high. The results showed that emissions were a factor of 2-5 higher when the stove temperature was increased from medium to high. This result implies that high temperature reduces food water or fat content more quickly, resulting in more rapid weight loss and thus a higher emission rate.

Some studies compared different types of stoves to see if stove fuel type influenced particle emission rates. Zhang et al performed repeated cooking experiments frying chicken on gas and electric types of ranges. The results showed that emissions from the use of the gas stove were a factor of 2 higher than an electric stove for the same cooking method. Buonanno et al. found that gas stoves generate more particles than electric when grilling. This result reflects the fact that indoor combustion, i.e. gas stove flames, is an important sources of particulate matter in the absence of cooking emissions. Gas stoves are also an important source of pollutants such as CO and $NO_X$ and can result in acute exposures at harmful concentrations.

Individual studies also showed that the type of oil used for cooking as well as the method of cooking influences particle emissions. Fullana et al.[28] showed that canola oil has relativity low emission rates of volatile aldehyde emissions compared to olive oil for high temperature frying. Moreover, a comparison of test [21] and test [30] in the Fortmann paper showed that cooking with vegetable oil results in greater PM emission than peanut oil.

## *Impact of Cooking Parameters on Database Emission Rates*

The results from the all of the studies included in the $PM_{2.5}$ cooking emission rate database were inter-compared to determine if the impact of HICCs seen in individual cooking studies could be discerned between the different cooking studies. The $PM_{2.5}$ emission rates were sorted into categories, as shown in Table 3, to understand the impact of specific HICCs. The data has been subdivided by food type, type of oil used, type of cooking, and type of appliance used reflecting the previously identified HICCs. In Figure 1 we fit log normal distributions to the summary statistics (geometric mean and geometric standard deviation) compiled in Table 3. The fits in Figure 1 are provided as a visual comparison of the data in Table 3. Given the limited amount of data, we cannot accurately fit distributions to the data.

Evaluating data from several studies increased the variability of the cooking setups compared. In a controlled setting where only one condition is varied, the impact of the identified HICCs may be large, but that impact may be small relative to the impact of the differences in cooking setups such as differences in stoves used and pan types and sizes among others.

As shown in Table 3, the food types showed similar ranges of emission rates. The distributions of emissions for the four food subdivisions overlap to a great extent. While several papers report different emission rates for different foods, the results in Table 3 show that, on average, cooking vegetables has similar emission rates to cooking meat. This

[28] Fullana, Carbonell-Barrachina, and Sidhu, "Volatile Aldehyde Emissions from Heated Cooking Oils."

may be due to the fact that vegetables are rarely cooked alone in the papers reviewed, and some of the vegetables in our database are stir fried with chicken. This similarity in emission rates for different food types indicates that other cooking variables have a larger impact of cooking emission rates.

*Table 3: PM2.5 emission rates (μg/hr)*

| **$PM_{2.5}$ Emission Rates** | Number of studies | Cooking Tests | Arithmetic mean | Arithmetic STDEV | Geometric mean | Geometric STDEV |
|---|---|---|---|---|---|---|
| Food type | | | | | | |
| Red meat | 1 | 21 | 1.2E+05 | 0.8+05 | 8.0E+04 | 3.4E+00 |
| Poultry | 2 | 19 | 1.2E+05 | 1.7E+05 | 2.5E+04 | 1.3E+01 |
| Sea food | 1 | 6 | 2.3E+05 | 0.8E+05 | 2.2E+05 | 2.9E+00 |
| Vegetables | 3 | 16 | 1.6E+05 | 1.8E+05 | 7.6E+04 | 4.1E+00 |
| Type of oil | | | | | | |
| Vegetable oil | 1 | 8 | 2.2E+05 | 1.9E+05 | 1.5E+05 | 3.0E+00 |
| Olive oil | 2 | 7 | 6.6E+05 | 11E+05 | 3.2E+05 | 5.5E+00 |
| Peanut oil | 2 | 7 | 2.7E+05 | 2.0E+05 | 2.1E+05 | 3.3E+00 |
| Soybean oil | 1 | 1 | 3.4E+05 | | | |
| Corn oil | 2 | 15 | 1.2E+05 | 4.0E+05 | 7.5E+03 | 2.1E+01 |
| Type of cooking | | | | | | |
| Fried | 6 | 160 | 8.9E+04 | 32E+04 | 6.5E+03 | 9.6E+00 |
| Grilled | 3 | 6 | 1.7E+04 | 2.5E+04 | 4.0E+03 | 1.2E+01 |
| Oven | 1 | 38 | 6.3E+02 | 7.4E+02 | 3.7E+02 | 2.9E+00 |
| Type of appliance | | | | | | |
| Elec. Range/Oven | 4 | 317 | 1.1E+04 | 4.9E+04 | 1.3E+03 | 9. 1E+01 |
| Gas Range/Oven | 3 | 156 | 3.8E+04 | 9.3E+04 | 1.7E+03 | 1.0E+01 |
| Microwave | 1 | 21 | 6.4E+02 | 6.6E+02 | 3.2E+02 | 5.5E+00 |

There is a similar overlap in the emission rates measured for the different types of oil. The Type of oil section in Table 3 shows that olive oil has the largest average cooking emission rate but also has the largest standard deviation. Pan size, the surface area of the cooking oil, and cooking temperature should have a significant impact on emissions from cooling oils. These parameters, which are not recorded by any study, may dominate the variability in the emission rates.

For cooking type in Table 3, grilling and frying have significant overlap in the distribution of their emission rates while cooking in the oven appears to have lower average emissions rates and a narrower distribution. The type of appliance section in Table 3 shows overlapping distributions for gas and electric cooking but microwave cooking appears to have lower average emission rates and a narrower distribution.

Significant variability in emission rates were observed for replicate tests at the same conditions. For example, Fortmann et al showed factor of 2 changes in emission rates for repeat tests. However, larger differences were seen when cooking conditions changed. Variations larger than a factor of 350 were seen between different frying events by Olson et al. in different houses. These results indicated that the variability in the test setups or home kitchen setups have a large impact on the cooking emission rates. Emission rates are greatly influenced by temperature, food surface area to mass ratio, and tidiness of cooking appliance, parameters that are not routinely recorded and will not be easily assessed for the US housing stock.

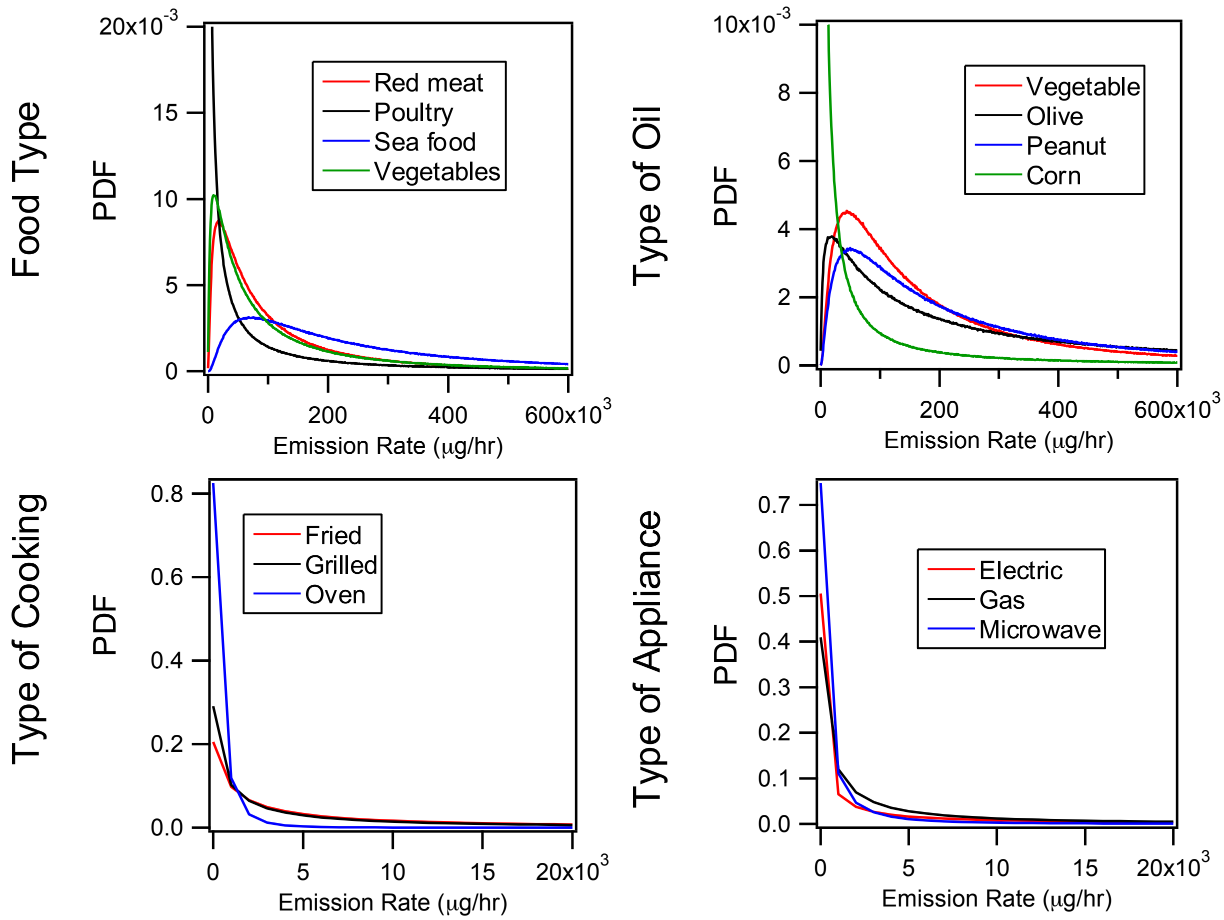


*Figure 1: Log-normal distributions of PM2.5 emission rates (μg/hr)*

## *Candle and Incense Emission Data*

In addition to cooking activities, indoor combustion activities such as candle and incense burning also generate significant $PM_{2.5}$. Glytsos et al. reported that candle burning has significant particle emission rates in the ultrafine range, and contribute to increased indoor $PM_{2.5}$ concentrations. The emission rate of a steady burning candle is primarily determined by its composition. For example Afshari et al. measured that burning of pure wax candles generated an ultrafine particle concentration twice as high as that of scented candles. In addition, Zai et al.[29] determined that candle-burning conditions affect their particle size distribution. Steady burning candles primarily produce ultrafine particles, while unsteady burning candles produce large amounts of black carbon particles. Zai et al. reported that an estimated one billion pounds of wax are used in the candles sold each year in the United

[29] Zai et al., "Studies on the Size Distribution, Number and Mass Emission Factors of Candle Particles Characterized by Modes of Burning"

States, and most of the candles are used indoors, so the impact of candle emissions on human health cannot be ignored.

While several papers discuss candle and incense emissions, only two papers were found that reported mass emissions per unit time for $PM_{2.5}$. The majority of existing candle studies report either PM10 emissions or particle number emissions. Table 4 presents a summary of the emission data from the studies that have been included in the emission rate database. In Figure 2 we fit log normal distributions to the summary statistics (geometric mean and geometric standard deviation) compiled in Table 4. Again, the fits in Figure 2 are provided as a visual comparison of the data in Table 4 only because the data it to limited to accurately fit distributions that are representative of incense and candle burning.

More research is needed to develop a comprehensive $PM_{2.5}$ emission rate database for candle burning. However, from this limited data set, it appears that the type of incense used impacts the emission rate and that candles have a significantly lower emission rate than incense or mosquito coils. It also appears that candle and incense emission rates are, on average, lower than cooking emission rates.

*Table 4: Candle and Incense $PM_{2.5}$ emission rates (μg/hr)*

| | ***Number of studies*** | ***Burning Tests*** | ***Arithmetic mean*** | ***Arithmetic STDEV*** | ***Geometric mean*** | ***Geometric STDEV*** |
|---|---|---|---|---|---|---|
| **Incense-stick** | 2 | 14 | 4.1E+01 | 2.9E+01 | 3.2E+01 | 7.2E-01 |
| **Incense-cone** | 1 | 4 | 9.2E+01 | 8.3E+01 | 6.2E+01 | 9.5E-01 |
| **Incense-joss stick** | 1 | 3 | 2.3E+01 | 1.0E+01 | 2.1E+01 | 3.6E-01 |
| **Incense-other** | 1 | 5 | 1.1E+02 | 0.6E+02 | 9.1E+01 | 5.3E-01 |
| **Candles** | 1 | 2 | 4.6E-01 | 5.9E-01 | 1.9E-01 | 2.8E+00 |
| **Mosquito coil** | 1 | 2 | 6.2E+01 | 3.7E+01 | 5.7E+01 | 4.5E-01 |

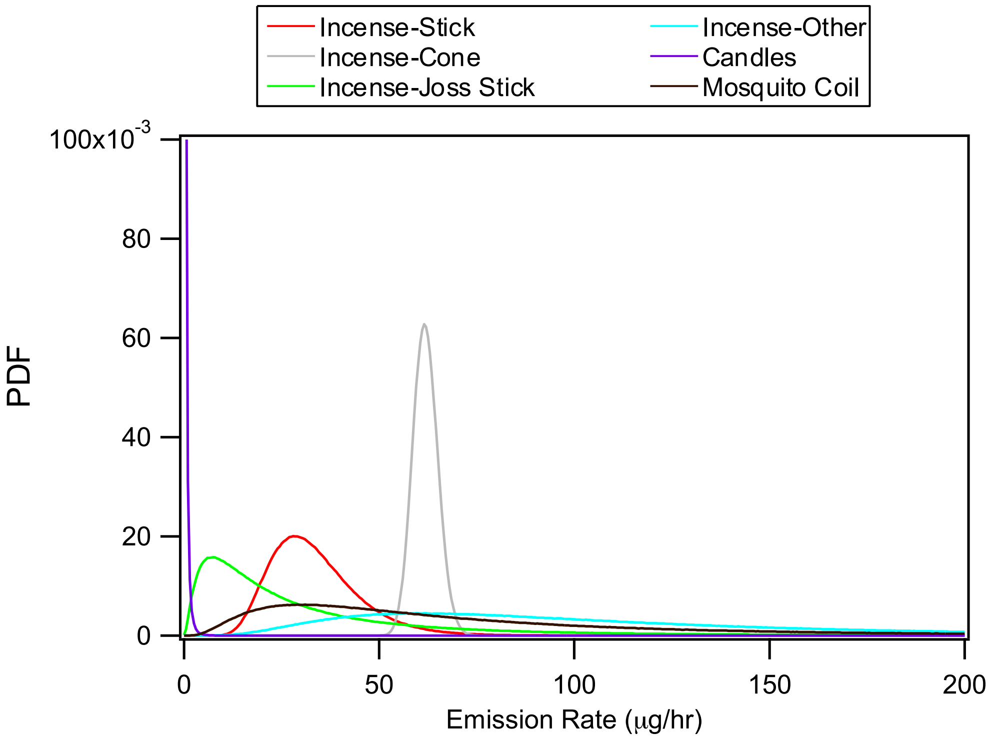


*Figure 2: Log-normal distributions of PM2.5 incense and candle emission rates (µg/hr)*

## *Using the PM2.5 Emission Rate Database in IERC Modeling*

The purpose of collecting the emissions data was to model exposure to occupants of the U.S. residential housing stock to develop cost effective strategies for providing good IAQ in homes. Logue et al.[30] wrote a data needs document for the modeling endeavor that stated that, based on the impact of cooking conditions in individual emissions studies, both the emission rate for specific types of cooking as well as the frequency of that type of cooking would be needed to estimate the impact of emissions on health. Our analyses of the emission rates database indicates that, of the HICCs identified in individual studies, only type of appliance and type of cooking impact the emission rate. This means that when we incorporate cooking in to the IERC model that only these parameters and the start and stop times for the cooking events are required to model the exposure.

Similar to the cooking emissions, there is significant overlap in distributions for emission rates of incense, however different types of incense appear to have a large impact on the emission rate. Candle emission rates appear to be lower than incense and mosquito coil emissions. Incorporating these emission rates into the IERC model will require knowledge of the frequency of candle and incense burning and, if possible, the type of incense used.

[30] Logue, Sherman, and Singer, "Healthy Efficient Homes: Data Needs to Support Development of a Health-Based Ventilation Standard. 2011."

# Conclusion

This paper reports the results of the initial efforts to develop an emission factors database for $PM_{2.5}$ emissions from cooking and candle and incense burning in U.S. residential environments. The work focused on collecting $PM_{2.5}$ emission rates but also included emission data for other pollutants included in cooking emissions studies. We conducted a literature review to aggregate existing data on emissions. Over 60 papers were reviewed and 15 studies had enough data to be included in the database. Thirteen papers reported cooking emissions and 2 reported candle and incense emissions. An annotated bibliography of the papers included in the database and papers that did not have emissions data, but were relevant to residential cooking and candle and incense burring, were included in the appendix. Unfortunately, the available emission rate data was rather limited with most studies reporting insufficient information on the conditions that impact emission rates. More cooking emissions tests combined with detailed recording of experimental conditions are needed to better quantify the impact of different cooking conditions on emission rate.

Individual studies indicated that food type, cooking oil type, and method of preparing food significantly impacted the emissions of cooking events. However, when the impact of these across all of the emission rate studies in the database were compared, we found that differences in food type and oil type did not have a significant impact on the emission rate. The type of cooking device used (i.e. microwave vs. stove) and the type of cooking (i.e. baking the oven vs. grilling and frying) resulted in distinctly different distributions of $PM_{2.5}$ cooking emission rates. The lack of differentiation between emission rates for the different food and oils may be due to other non-recorded parameters that varied between different papers.

The intent of the emission database is to use it in conjunction with behavioral data to determine the impact of cooking and candle and incense burning on health. The analysis of the current database indicates that only knowledge of the type of cooking device used and how the meal was prepared, as well as cooking start and stop times, is necessary for modeling indoor cooking $PM_{2.5}$ exposures. Similarly, the only data necessary to model exposures to candles and incense burning are when and how many are used. As more detailed emissions data becomes available it may be necessary to know more characteristics of behavior to accurately model exposures.

# Appendices

## ANNOTATED BIBLIOGRAPHY OF COOKING STUDIES

Abt, E, H H Suh, G Allen, and P Koutrakis. "Characterization of Indoor Particle Sources: A Study Conducted in the Metropolitan Boston Area." *Environmental Health Perspectives* 108, no. 1 (January 2000): 35–44.

In this article Abt et al. focused on indoor particles sources and size distributions. Indoor and outdoor real-time particle concentrations and size measurements were carried out in order to understand how seasonal factors and air exchange rates influence the indoor-outdoor particle concentration. Diurnal indoor particle concentrations are measured to demonstrate the impact of different indoor activities, such as cooking and cleaning. The results did not report a cooking emission rate, only a maximum concentration during cooking. Since the duration of the cooking event was not included, we could not calculate the emission rate to include in the database.

Afshari, A., U. Matson, and L. E Ekberg. "Characterization of Indoor Sources of Fine and Ultrafine Particles: a Study Conducted in a Full-scale Chamber." Indoor Air 15, no. 2 (February 28, 2005): 141–150.

This research carried out by Afshari et al. measured the emission rates of ultrafine and fine particle from 13 different particle sources, such as candles, heaters, stoves, etc in a full-scale chamber. Results showed that the increase of the particle concentration immediately after activation of the source was more rapid than the decay of the concentration observed after deactivation of the source. The highest and lowest generation rate are respectively observed from a radiator test and ironing without stream on a cotton sheet. The combustion of a pure wax candle gives the highest concentration, approximately 241,000particles/cm3 . This paper reports valuable information on the order of magnitude of the emission rates for some indoor activities. The paper also identified that burning candles, cigarette smoke, frying, gas stove use, ironing with steam on a cotton sheet, vacuum cleaner use and air-freshener spray are primary sources of ultrafine particles. However, electric radiators, electric heaters, electric stoves and ironing without steam are not considered primary sources unless dirt or dust has accumulated on the heated surfaces.

This paper reports particle number emission rates and not mass emission rates, therefore the data was not included in our database. This paper would be a useful source of data for modeling particle counts in homes.

Ashman, P. J., R. Junus, J. F. Stubington, and G. D. Sergeant. "The Effects of Load Height on the Emissions from a Natural Gas-Fired Domestic Cooktop Burner." Combustion Science and Technology 103, no. 1–6 (1994): 283–298.

The thermal efficiency of a cook top depends on its load height. The smaller the distance between the pot and the burner, the more energy will be transferred to the pot. However, without sufficient distance between the pot and the burner, the pot may inhibit complete combustion of natural gas resulting in high CO emissions. In order to provide good indoor air quality, we should be aware of the influence of load height on the emission rate of CO, NO, etc. and provide a means of assessing the "balance" between the requirements for lower emission rates and higher thermal efficiency. This paper provides useful information for stove manufacturer about how to improve their thermal efficiency without increasing the health impact from emissions.

Bhangar, S., N. A. Mullen, S. V. Hering, N. M. Kreisberg, and W. W. Nazaroff. "Ultrafine particle concentrations and exposures in seven residences in northern California RID B-1906-2012." Indoor Air 21, no. 2 (April 2011): 132–144.

In this article, Bhangar et al. focused on ultrafine particle number concentrations and exposures in seven residences. They carried out a series of particle number measurements, however they did not measure mass concentrations or emission rates therefor the paper was not included in the database. Bhangar et al determined that cooking results in the highest peak of particle number concentration, and that human activities have a significant effect on indoor particle concentrations. During the period when occupants were awake, particle number levels were on average 6.6 times greater than particle number levels when occupants were asleep.

Buonanno, G., L. Morawska, and L. Stabile. "Particle emission factors during cooking activities." Atmospheric Environment 43, no. 20 (June 2009): 3235–3242.

Buonanno et al. aimed to evaluate the influence of the temperature, food, cooking oil and oven type on the number, surface area and mass particulate emission factors when frying and grilling. Results showed that the gas stove generated more particles than the electric stove when grilling; foods containing a higher percentage of fat generated higher emission rates; and particle number, surface area and mass concentration all increased for higher cooking temperatures for both gas and electric stoves. In addition, sunflower oil generated the lowest number, surface area and mass emission ratess, while olive oil emits the highest. These data are included in the database.

Buonanno, G., G. Johnson, L. Morawska, and L. Stabile. "Volatility Characterization of Cooking-Generated Aerosol Particles." Aerosol Science and Technology 45, no. 9(2011): 1069–1077.

In this article, Buonanno et al. reviewed the characteristic of cooking generated aerosol particles. They measured the amount of volatile material emitted by different cooking activities (frying and grilling). However, there is no PM mass emission measurements and therefore the paper did not yield any data to be included in the database.

Chao, Christopher Y, and Eddie C Cheng. "Source Apportionment of Indoor $PM_{2.5}$ and PM10 in Homes." Indoor and Built Environment 11, no. 1 (January 1, 2002): 27–37.

This report analyzed the indoor $PM_{2.5}$ and PM10 sources in 8 homes in Hong Kong . They focused on five common particle sources: smoking, cooking, incense burning, human activities and outdoor contribution. The results showed that $PM_{2.5}$ and PM10 have different source apportionments indicating the importance of different sources to the indoor $PM_{2.5}$ and PM10 concentration. Cooking is the most important source of indoor $PM_{2.5}$ and contributes an average of 61.9% of the total mass. An average of 21.9% of the $PM_{2.5}$ mass comes from outdoors. On the contrary, PM10 is generally from outdoor source and mainly influenced by human activities. PM10 deposits quicker to the horizontal surfaces by gravitational settling and can also be remixed with air by human activities (movement cleaning etc.). They conducted an inorganic element analyze for four indoor sources, and this part of data can be added into our database for later research.

Dennekamp, M., S. Howarth, C a J Dick, J W Cherrie, K. Donaldson, and A. Seaton. "Ultrafine Particles and Nitrogen Oxides Generated by Gas and Electric Cooking." Occupational and Environmental Medicine 58, no. 8 (August 1, 2001): 511–516.

In this research, Dennekamp et al. measured particulate and nitrogen oxide concentrations during a series of indoor cooking experiments. Results showed that high concentrations of particles are generated by gas combustion, frying and fatty cooking. Results indicated that poorly ventilated kitchens could result in high concentrations of oxides of nitrogen and could potentially impact human health. We have included their NO and $NO_2$ emission rates in our database.

Evans, G. J, A. Peers, and K. Sabaliauskas. "Particle dose estimation from frying in residential settings." Indoor Air 18, no. 6 (December 2008): 499–510.

In this research, Evans et al. reviewed production rates of ultra-fine particulates (UFPs) and $PM_{2.5}$ from frying different foods in a single home and the emission rates of UFPs and $PM_{2.5}$ from frying vegetable oil in five different homes. The emission rates that they determined are included in the database.

Fortmann, R., Kariher, P. and Clayton, C. Indoor Air Quality: Residential Cooking Exposures. California Air Resources Board Final Report (2001).

In this report, Fortmann et al. carried out a series of residential cooking emission studies. They measured the emission rates of PM, CO, NO, $NO_2$ and a subset of other pollutants during 39 cooking tests. Different cooking conditions, such as cooking temperatures, oil, and range and oven types, have been compared. Real-time $PM_{2.5}$ concentrations and size distributions where reported for each cooking test. These detailed data are exactly what we are searching for and we have included them in our cooking emission database. Moreover, they compared the data acquired in the various tests, and included a significant amount of useful information about cooking emission characteristics in chapter 4 .

Francisco, P. W, J. R Gordon, and B. Rose. "Measured Concentrations of Combustion Gases from the Use of Unvented Gas Fireplaces." Indoor Air 20, no. 5 (April 16, 2010): 370–379.

This is not a report related to cooking emission studies. They reviewed a limited set of harmful gas (CO, NO, $NO_x$, $NO_2$) and water vapor exposure in homes that used an unvented gas fireplace.

Fullana, Andres, Ángel A Carbonell-Barrachina, and Sukh Sidhu. "Volatile Aldehyde Emissions from Heated Cooking Oils." Journal of the Science of Food and Agriculture 84, no. 15 (August 25, 2004): 2015–2021.

Cooking has been shown to be one of the main sources of indoor particle pollution. In this report, Fullana et al. focused on the emission of aldehydes from heated cooking oils. They found that the formation of aldehydes during deep-frying operations depends mainly on temperature. At a temperature of 180 ◦C (below the smoke point of olive and canola oils), the use of olive oils in deep-frying operations will decrease the generation of volatile aldehydes. The paper recommended using canola oils for high temperature frying, since canola oil has a higher smoke point. The emission rate of aldehydes during the oil-heating procedure is provided in this paper; however the method of heating the oil is very different than conditions that would be expected in home cooking. Because of this, the reported emission rates were not included in our database.

He, Congrong, Lidia Morawska, Jane Hitchins, and Dale Gilbert. "Contribution from Indoor Sources to Particle Number and Mass Concentrations in Residential Houses." Atmospheric Environment 38, no. 21 (July 2004): 3405–3415.

In this article, He et al. tested 21 kinds of indoor activities in Brisbane Australia; and measured and compared their particle emission rates. Their results show that frying, grilling, stove use, toasting, cooking pizza, cooking, vaporizing eucalyptus oil and fan heater use could elevate the indoor sub micrometer particle number concentration levels by more than a factor of 5. $PM_{2.5}$ concentrations could also be up to 3, 30 and 90 times higher than the background levels during smoking, frying and grilling. Within their report, the emission rates of certain activities have been compared to data from previous studies, where we can find obvious differences. This implies that, the emission rates of indoor activities vary greatly from home to home and event to event, and the emission rate depends greatly on the cooking conditions during the measurement. The data from this study has been included in our database.

Huboyo, Haryono S., Susumu Tohno, and Renqiu Cao. "Indoor $PM_{2.5}$ Characteristics and CO Concentration Related to Water-Based and Oil-Based Cooking Emissions Using a Gas Stove." Aerosol and Air Quality Research 11, no. 4 (August 2011): 401–411.

Huboyo et al. carried out experiments in Japan, in order to study the indoor $PM_{2.5}$ and CO exposures originating from two distinctive cooking methods: frying and boiling. Results show that PM and CO can be found in the kitchen and adjoining room during cooking activities; however the adjoining room has lower concentrations. Frying produces more fine particles with a wider range of aerodynamic sizes than boiling, but low frying temperature can help to reduce the oil mist emissions. CO concentrations were lowest in tofu boiling; this is possibly due to the absorption of CO by steam cooking.

Their measured PM and CO concentrations are expressed by a range during the cooking activates. The study did not provide sufficient information about the experimental setup to determine the emission rates of the cooking events and was therefore not included in database.

Jacob D. McDonald, Barbara Zielinska, Eric M. Fujita, John C. Sagebiel, Judith C Chow, and John G Watson. "Emissions from Charbroiling and Grilling of Chicken and Beef." Journal of the Air & Waste Management Association (1995) 53, no. 2 (February 2003): 185–194.

Jacob et al. focused on emission rates during meat cooking. They compared 3 cooking styles: Auto- char broil, under- char broil, and griddle, when cooking beef and chicken.

Their results showed that, charbroiling emission yielded an average of 3-5 times more polycyclic aromatic hydrocarbons (PAH)s, about 20 times more cholesterol, and about 10 times more lactones than grilling. For the 6 categories of tests they carried out, detailed emission rates of various organic compounds were provided, which have been included in our database. This paper also includes a discussion on the formation of the measured chemical compounds.

J.M. Burke; Zufall, M.J.; and ̈Zkaynak H. "A Population Exposure Model for Particulate Matter: Case Study Results for $PM_{2.5}$ in Philadelphia, PA" Journal of Exposure Analysis and Environmental Epidemiology (2001)11, 470–489

This paper described the structure of the SHEDS-PM model, the algorithms used to estimate personal exposure and the input database including micro environmental data and population/demographic data. This paper compared the $PM_{2.5}$ emission rate from cooking, smoking and other activities during the day and night, however there is no specific information about the cooking and smoking conditions, food species and cooking appliance used. We have included the estimated distribution of cooking emissions from this study in our database.

Kabir, Ehsanul, and Ki-Hyun Kim. "An investigation on hazardous and odorous pollutant emission during cooking activities." Journal of Hazardous Materials 188, no. 1–3 (April 15, 2011): 443–454.

The emission characteristics of various pollutions (19 out of 22 compounds included in the mal-odor law in South Korea) were investigated due to cooking 3 kinds of food using 2 cooking techniques. They focused on the odorous compound concentrations and the odor intensity distribution. They found significant correlations between concentrations of many volatile organic compounds (VOCs). They point out that the high lung cancer rate of Chinese women is suspected to be associated with using unrefined rapeseed oils for cooking. To evaluate the potential health effects from indoor air exposure, it is necessary to have further studies on the duration, frequency, and intensity of exposure.

Their measurements of indoor pollutants concentration used a Tedlar sample collection bag to capture the exhaust and reported the measured concentration in the bag. The study does not report sufficient information about the sampling technique to determine emission rates from the data provided.

Kamens, Richard, Chung-te Lee, Russell Wiener, and David Leith. "A Study of Characterize Indoor Particles in Three Non-smoking Homes." Atmospheric Environment. Part A. General Topics 25, no. 5–6 (1991): 939–948.

This study, carried out in north California, analyzed the aerosol concentration and particle size distributions in three middle-income homes. Their measurement results have showed that particulate concentration in the three homes ranged from 14-42μg/m$^3$, and 37% of the mass was collected in the fine (2.5μm aerodynamic diameter or below) fraction. Further more, measurements proved that cooking is the most significant small particle generation event, in both the "less than 0.10μm" and the "1-2μm" ranges. These experiments emphasize the important role cooking events play in indoor $PM_{2.5}$ emissions. Kamens et al also reported that particles below 1μm dominate the particle size-number distribution and biological and mineral based particles predominantly make up the 2.5-10μm-size range. This is a valuable report for our study although it contains no data of specific mass emission rates and was therefore not included in our database.

Moschandreas, D., S. Relwani, D. Johnson, and I. Billick. "Emission Rates from Unvented Gas Appliances." Environment International 12, no. 1–4 (1986): 247–253.

This is a report of indoors test of unvented gas appliances. No emission rate of indoor activities provided, exclude from database.

McDonald, Jacob D, Barbara Zielinska, Eric M Fujita, John C Sagebiel, Judith C Chow, and John G Watson. "Emissions from Charbroiling and Grilling of Chicken and Beef." Journal of the Air & Waste Management Association (1995) 53, no. 2 (February 2003): 185–194.

Meat cooking is a source of atmospheric air pollution. In this article McDonald et al. reviewed the emission rate of CO, organic and elemental carbon and inorganic species from charbroiling hamburger, steak, and chicken. They found that emission rates varied by type of appliance, meat type, meat-fat content, and cooking conditions. High-fat hamburger cooked on an under fired char broiler emitted the highest amount of $PM_{2.5}$. Although they did not provide any PM emission rates in this paper, their numerous data of CO, and other organic/inorganic species emission rate are also very valuable to us and have been included in our database.

Seaman, Vincent Y., Deborah H. Bennett, and Thomas M. Cahill. "Indoor acrolein emission and decay rates resulting from domestic cooking events." Atmospheric Environment 43, no. 39 (December 2009): 6199–6204.

Previous studies have proved that acrolein can be produced from incomplete combustion of organic material as well as the oxidation of atmosphere chemicals, and can result in asthma in children and lung cancer. This study carried out by Seaman et al. intended to determine the acrolein emission rate from different types of cooking oils and food items. Their experiments are also helpful to understand the relation between air exchange rate and the overall removal rate of indoor pollutants. The paper reported emission rates for a variety of foods cooked in soybean oil and cooked one item, donuts, in 4 oils and with a control for comparison. Their numerous data of cooking emission rates is very useful for our research and the data has been included in our database.

Seaman, Vincent Y., Deborah H. Bennett, and Thomas M. Cahill. "Origin, occurrence, and source emission rate of acrolein in residential indoor air." Environmental Science & Technology 41, no. 20 (October 15, 2007): 6940–6946.

This report focused on indoor acrolein concentrations; no PM emission or concentrations were measured. They found acrolein levels in evening samples up to 2.5 times higher than morning samples, and homes with frequent, regular cooking activity had the highest baseline (morning) acrolein levels. The emission rates determined by Seaman et al for acrolein were included in the database.

Schauer, James J., Michael J. Kleeman, Glen R. Cass, and Bernd R. T. Simoneit. "Measurement of Emissions from Air Pollution Sources. 1. C1 through C29 Organic Compounds from Meat Charbroiling." Environ. Sci. Technol. 33, no. 10 (1999): 1566–1577.

Schauer et al. used a dilution source sampling system to quantify the organic air pollutant emission from commercial-scale meat charbroiling operations. Although this is not a residential cooking experiment, they have provided the duration of the test and data is expressed in μg/kg meat cooked. We were able to convert the reported emission factors into emission rates in μg/hour per kg of meat cooked. For the emissions rates to be useable in future modeling endeavors we will multiply the emission rate by the amount of meat cooked per household. The rate of meat cooking can be estimated as a function of home size using the EPA's Emission Factors Handbook[31].

The number of kinds of food in their test is relativity small (only hamburger emissions). We have included their data as a hamburger cooking emission rate. As is noted in the paper, some measurements (n-alkanoic acids) are limited by the filter they were using; further future experiments may have more accurate emissions data.

Thiébaud, H.P., M.G. Knize, P.A. Kuzmicky, D.P. Hsieh, and J.S. Felton. "Airborne Mutagens Produced by Frying Beef, Pork and a Soy-based Food." Food and Chemical Toxicology 33, no. 10 (October 1995): 821–828.

This report of a cooking mutagenic study showed that different type of food affects the level of mutagenicity in cooked food and related fumes. Results have shown that, bacon fried was 8-times more mutagenic from frying hamburgers, and 350 times more mutagenic than tempeh burgers (soy-based). Moreover, they have found out that, at the same level of frying temperature, the bacon lost 76% of its weight, compared to 37-45% and 11% for hamburger and tempeh burgers. In conclusion, mutagenicity of the cooked food samples appears to be correlated to the loss of water, which induces a loss of weight and directly depends on the cooking temperature, the type of food and its surface area to weight ratio. This shows us that food weight loss maybe a new direction of cooking emission mutagenic studies. No data of emission rate available, exclude from database.

Wallace, Lance A, Steven J Emmerich, and Cynthia Howard-Reed. "Source Strengths of Ultrafine and Fine Particles Due to Cooking with a Gas Stove." Environmental Science & Technology 38, no. 8 (April 15, 2004): 2304–2311.

Cooking is one of the most important sources of particles indoors. In this paper, Wallace et al. focused on a full-range (in 124 size bins from 0.01 to 2.5μm) of ultrafine and fine particles sizes, during cooking events. This experiment is carried out in an occupied house for 18 month. They determined that frying events have the highest particle emission rate. Frying was capable of increasing the total particle production due to cooking by factors of

[31] "Exposure Factors Handbook| Human Health Risk Assessment | Risk Assessment Portal | US EPA."

6-10. Other experiments show that during cooking, the smallest ultrafine particles (10-18nm) were elevated by factors of 13-14 over backgrounds, the next smallest category (18-50nm) by factors of 7-9, whether number or mass concentrations are the metric. This paper is useful for us in explaining the significant influence on indoor air quality due to cooking events; however the data in the paper is not presented in a way that can be inputted into our database. We have contacted the authors and hope to add the data to the database in the near future.

Zhang, Qunfang, Roja H. Gangupomu, David Ramirez, and Yifang Zhu. "Measurement of Ultrafine Particles and Other Air Pollutants Emitted by Cooking Activities." International Journal of Environmental Research and Public Health 7, no. 4 (April 2010): 1744–1759.

In this article, Zhang et al. conducted ultrafine particle measurements during indoor cooking activities. Experiments show that cooking emissions show a strong dependence on cooking styles and parameters. They measured higher UFP concentration during frying than boiling, during gas stove than electric stove use; and when higher cooking temperatures were used. In addition, exhaust fan use had the most influence on the decay rate. Turning on the fan increased the decay rate by a factor of 2. We have included their $PM_{2.5}$ emission rates during Indian, Italian, Chinese, and American style cooking events in our database.

## ANNOTATED BIBLIOGRAPHY OF CANDLES AND INCENSE BURNING STUDIES

Afshari, A, U Matson, and L E Ekberg. "Characterization of Indoor Sources of Fine and Ultrafine Particles: a Study Conducted in a Full-scale Chamber." *Indoor Air* 15, no. 2 (April 2005): 141–150.

In this article, Afshari et al. reviewed indoor fine and ultrafine particles sources such as cigarette smoke, candles, vacuum cleaners, air-freshener spray, flat irons (with and without steam) on a cotton sheet, electric radiators, electric stoves, gas stoves, and frying meat. In most of the experiments the maximum concentration was reached within a few minutes because the generation rate of particles is much faster than decay rate after deactivation of sources. The highest concentration of ultrafine particles was observed to be approximately 241,000 particles/$cm^3$ and originated from the combustion of pure wax candles. Their findings agreed with those of Fine et al. (1999) and Cole (1998), that particles from candle burning are ultrafine particles (0.01 to 0.2 μm) and have less possibility to condense when a candle is lit.

Géhin, Evelyne, Olivier Ramalho, and Séverine Kirchner. "Size Distribution and Emission Rate Measurement of Fine and Ultrafine Particle from Indoor Human Activities." *Atmospheric Environment* 42, no. 35 (November 2008): 8341–8352.

In this report, Enelyne et al. focused on both size distribution and emission rate measurement of indoor particles. They compared their measurement results to those obtained from literature, few differences have been found due to different experiment set ups. They emphasized that cooking meat or fish on a stove or in an oven and during the pyrolysis cleaning can result in high particle emission rates. They have reviewed the characteristic between particle diameter and their emission rate, which can be useful from future particle sizing studies.

Glytsos, T., J. Ondráček, L. Džumbová, I. Kopanakis, and M. Lazaridis. "Characterization of Particulate Matter Concentrations During Controlled Indoor Activities." *Atmospheric Environment* 44, no. 12 (April 2010): 1539–1549.

This experiment carried out by Glytsos et al. reviewed the particulate matter concentration during various indoor activities, including candle burning, hot plate heating, water boiling, onion frying, vacuuming, hair drying, hair spraying, smoking and burning of incense stick. They showed that candle burning was the strongest among the sources of particulate matter and also presented the highest values of particles emission rates. They measured candle smoldering $PM_{2.5}$ mass concentration values higher than 300 mg/m$^3$, indicating the importance of candle emission during steady burning and smolder when the candle is not fully extinguished. In addition, they also mention the use of hair spray can lead to high $PM_{2.5}$ mass concentrations.

Jetter, James J, Zhishi Guo, Jenia A McBrian, and Michael R Flynn. "Characterization of Emissions from Burning Incense." The Science of the Total Environment 295, no. 1–3 (August 5, 2002): 51–67.

In this article, Jetter et al. carried out a series of measurement of 23 different types of incense, which are distinguished by their shape, producing area, and ingredients. They provided specific $PM_{2.5}$ and $PM_{10}$ particle emission rates in their report, which have been included in our database. They stated that incense smoke can pose a health risk to people due to inhalation exposure of particulate matter. Especially when exposure duration is long, room ventilation is low, room size is small, burning time of the incense is long, and emissions are high. They also studied gas pollutant emissions (CO NO $SO_2$, etc.) and their indoor concentration can exceed outdoor standards specified by the NAAQS under certain conditions.

Stabile, L., F.C. Fuoco, and G. Buonanno. "Characteristics of Particles and Black Carbon Emitted by Combustion of Incenses, Candles and Anti-mosquito Products." *Building and Environment* 56, no. 0 (October 2012): 184–191.

In this article, Stabile et al. conducted a particle and black carbon emission study of indoor combustion activities, they conducted a series of 5 minute burning tests of incense (freesia, citronella, and church), candles (paraffin wax candle and natural corn wax candle) and anti-mosquito products (Mosquito coil and citronella stick). They found that particle number and PM fractions emitted during incense and anti-mosquito product burning (smoldering combustion) were comparable to typical cooking activity emissions. Candle combustion, during full flaming combustion, produced fewer particles and the particles were mainly carbonaceous. They also found that flaming combustion activity (paraffin candle burning) emitted in the ultrafine size range, which illustrated the important role of candle burning in indoor PM studies. They also mentioned that more than 80% of the mass of $PM_{10}$ particles in candle burning is made up of black carbon. Emission results from this paper were included in the database.

Zai, Sun, Huang Zhen, and Wang Jia-song. "Studies on the Size Distribution, Number and Mass Emission Factors of Candle Particles Characterized by Modes of Burning." *Journal of Aerosol Science* 37, no. 11 (November 2006): 1484–1496.

This research specifically focused on particle emission from different candle burning modes, including steady burn, unsteady burn and smoldering. They found some interesting differences: a steady burning candle contains a large number of ultrafine particles, however it contributes little to the particle mass concentration; an unsteady burning candle produces a black smoke size distribution which is bimodal in the 10–500 nm range and has a significant contribution to mass concentration. A smoldering candle hardly consumes any mass due to the short duration of the smoldering phase, however during that phase smoldering emits significantly high particle number and mass rates. This report will help us to understand the characteristic of the candle burning process, however does not appear be useful for our indoor air quality emission factor database.

# Additional References

Albalak, R., N. Bruce, J. P. McCracken, K. R. Smith, and T. De Gallardo. “Indoor respirable particulate matter concentrations from an open fire, improved cookstove, and LPG/open fire combination in a rural Guatemalan community.” Environmental Science & Technology 35, no. 13 (July 1, 2001): 2650–2655.

Balakrishnan, K., J. Parikh, S. Sankar, R. Padmavathi, K. Srividya, V. Venugopal, S. Prasad, and V. L. Pandey. “Daily average exposures to respirable particulate matter from combustion of biomass fuels in rural households of southern India.” Environmental Health Perspectives 110, no. 11 (November 2002): 1069–1075.

Abt, Eileen, Helen H. Suh, George Allen, and Petros Koutrakis. “Characterization of Indoor Particle Sources: A Study Conducted in the Metropolitan Boston Area.” Environmental Health Perspectives 108, no. 1 (January 1, 2000): 35–44.

Afshari, A, U Matson, and L E Ekberg. “Characterization of Indoor Sources of Fine and Ultrafine Particles: a Study Conducted in a Full-scale Chamber.” Indoor Air 15, no. 2 (April 2005): 141–150.

Buonanno, G., L. Morawska, and L. Stabile. “Particle emission factors during cooking activities RID B-4140-2011.” Atmospheric Environment 43, no. 20 (June 2009): 3235–3242.

Chao, Christopher Y, and Eddie C Cheng. “Source Apportionment of Indoor $PM_{2.5}$ and PM10 in Homes.” Indoor and Built Environment 11, no. 1 (January 1, 2002): 27–37.

EnVIE. “Co-ordination Action on INdoor Air Quality and Health Effects” (2004).

EPA. “National Ambient Air Quality Standards (NAAQS)” (February 24, 2010). http://www.epa.gov/air/criteria.html.

“Exposure Factors Handbook| Human Health Risk Assessment | Risk Assessment Portal | US EPA”, n.d. http://www.epa.gov/ncea/efh/report.html.

Fullana, Andres, Ángel A Carbonell-Barrachina, and Sukh Sidhu. “Volatile Aldehyde Emissions from Heated Cooking Oils.” Journal of the Science of Food and Agriculture 84, no. 15 (August 25, 2004): 2015–2021.

He, CR, LD Morawska, J Hitchins, and D Gilbert. “Contribution from indoor sources to particle number and mass concentrations in residential houses.” Atmospheric Environment 38, no. 21 (July 2004): 3405–3415.

Huboyo, Haryono S., Susumu Tohno, and Renqiu Cao. "Indoor PM(2.5) Characteristics and CO Concentration Related to Water-Based and Oil-Based Cooking Emissions Using a Gas Stove." Aerosol and Air Quality Research 11, no. 4 (August 2011): 401–411.

Jetter, James J, Zhishi Guo, Jenia A McBrian, and Michael R Flynn. "Characterization of Emissions from Burning Incense." The Science of the Total Environment 295, no. 1–3 (August 5, 2002): 51–67.

Kabir, Ehsanul, and Ki-Hyun Kim. "An investigation on hazardous and odorous pollutant emission during cooking activities." Journal of Hazardous Materials 188, no. 1–3 (April 15, 2011): 443–454.

Kamens, Richard, Chung-te Lee, Russell Wiener, and David Leith. "A Study of Characterize Indoor Particles in Three Non-smoking Homes." Atmospheric Environment. Part A. General Topics 25, no. 5–6 (1991): 939–948.

Künzli, N, Jerrett, M, Mack, WJ, Beckerman, B, LaBree, L, Gilliland, F, et al. 2004. Ambient Air Pollution and Atherosclerosis in Los Angeles. Environ Health Perspect 113(2).

Logue, J M, T E McKone, M H Sherman, and B C Singer. "Hazard Assessment of Chemical Air Contaminants Measured in Residences." Indoor Air 21, no. 2 (April 2011): 92–109.

Logue, Jennifer M, Phillip N Price, Max H Sherman, and Brett C Singer. "A Method to Estimate the Chronic Health Impact of Air Pollutants in US Residences." Environmental Health Perspectives 120, no. 2 (February 2012): 216–222.

McDonald, Jacob D, Barbara Zielinska, Eric M Fujita, John C Sagebiel, Judith C Chow, and John G Watson. "Emissions from Charbroiling and Grilling of Chicken and Beef." Journal of the Air & Waste Management Association (1995) 53, no. 2 (February 2003): 185–194.

Michael S, Breen, Breen Miyuki, Long Thomas C, Willams Ronald W, and Schultz Bradley D. "Air Pollution Exposure Model for Individuals (EMI) in Health Studies: Evaluation of Indoor Air Quality Model for Particulate Matter", n.d.

Miller, KA, Siscovick, DS, Sheppard, L, Shepherd, K, Sullivan, JH, Anderson, GL, et al. 2007. Long-Term Exposure to Air Pollution and Incidence of Cardiovascular Events in Women. New England Journal of Medicine 356(5): 447-458.

Olson, David A., and Janet M. Burke. "Distributions of $PM_{2.5}$ Source Strengths for Cooking from the Research Triangle Park Particulate Matter Panel Study." Environ. Sci. Technol. 40, no. 1 (2005): 163–169.

Pope, CA, Burnett, RT, Thun, MJ. 2002. Lung Cancer, Cardiopulmonary Mortality, and Longterm Exposure to Fine Particulate Air Pollution. Journal of the American Medical Association

287(9): 1132-1141.

Samet, Jonathan M. "Indoor Air Pollution: A Public Health Perspective." Indoor Air 3, no. 4 (1993): 219–226.

Schlesinger, R.B., The health impact of common inorganic components of fine particulate matter (PM2.5) in ambient air: A critical review. Inhalation Toxicology, 2007. 19(10): p. 811-832.

Seaman, Vincent Y., Deborah H. Bennett, and Thomas M. Cahill. "Indoor acrolein emission and decay rates resulting from domestic cooking events." Atmospheric Environment 43, no. 39 (December 2009): 6199–6204.

"The National Human Activity Pattern Survey (NHAPS): a Resource for Assessing Exposure to Environmental Pollutants." Journal of Exposure Science and Environmental Epidemiology 11, no. 3 (2001). http://www.nature.com/jes/journal/v11/n3/full/7500165a.html.

Thiébaud, H.P., M.G. Knize, P.A. Kuzmicky, D.P. Hsieh, and J.S. Felton. "Airborne Mutagens Produced by Frying Beef, Pork and a Soy-based Food." Food and Chemical Toxicology 33, no. 10 (October 1995): 821–828.

Weisel, C. P., J. F. Zhang, B. J. Turpin, M. T. Morandi, S. Colome, T. H. Stock, D. M. Spektor, et al. "Relationship of Indoor, Outdoor and Personal Air (RIOPA) Study: Study design, methods and quality assurance/control results." Journal of Exposure Analysis and Environmental Epidemiology 15, no. 2 (March 2005): 123–137.

Zhang, Qunfang, Roja H. Gangupomu, David Ramirez, and Yifang Zhu. "Measurement of Ultrafine Particles and Other Air Pollutants Emitted by Cooking Activities." International Journal of Environmental Research and Public Health 7, no. 4 (April 2010): 1744–1759.